Customer-End Inverter in an LVDC Distribution Network

Pasi Nuutinen, Pasi Salonen, Pasi Peltoniemi, Pertti Silventoinen

Abstract — **An AC-based low-voltage distribution network can in some cases be replaced with a low-voltage direct current (LVDC) network. With a higher DC voltage, the transmission capacity increases compared with the AC system with the same cable cross-sectional area. The DC link feeds an inverter that converts the DC voltage to a 230 V single-phase or 400 V three-phase AC voltage. Because the three-phase voltage is not necessarily needed in most residential applications, this paper presents two single-phase inverter topologies. Inverter modulation and its suitability for this kind of an application is discussed. The inverter efficiency and its requirements are also discussed in brief, yet more precise analyses are left for future studies. The conclusion is that a half-bridge topology is not suitable for this application, and therefore, a full-bridge inverter should be used instead.**

***Index Terms*—Distribution network, LVDC, single-phase inverter**

I. INTRODUCTION

A low-voltage distribution network is traditionally based on a three-phase 400 V AC system. Because of the low voltage, 20/0.4 kV transformers have to be installed close enough to the customer to avoid too high transmission losses. The use of a higher AC or DC voltage in the LV network increases the power transmission capacity and enables longer distances. Some parts of this AC system can be replaced with a DC or AC system with a higher voltage, because the Low Voltage Directive LVD 72/23/EEC [1] covers equipment designed for use with voltage ratings 50–1000 VAC and 75–1500 VDC. In some Nordic countries, 1000 VAC system has been successfully applied in some parts of the LV network. The use of a higher AC voltage level increases the transmission capacity of an aerial or underground cable with the same cross-section area [2], [3], [4].

At present, there is an ongoing study in which direct current is considered in power transmission between a 20 kV distribution network and the customers. At the customer, a single-phase or a three-phase inverter is used in the DC/AC conversion. Figure 1 presents two alternatives for an LVDC system that replaces the AC system. The first system consists of a single inverter that feeds a short AC network, whereas in the second option, there are separate inverters for every individual customer. In both topologies, the DC link between a rectifier and an inverter can be similar [5]. As can be seen in Fig. 1, the DC distribution network also constitutes a protection zone of its own. This decreases the coverage area of the fault, because with a DC link fault, the link can be disconnected from the MV network. With an AC system, the fault is very often in the MV network, and therefore a larger part of the MV network has to be disconnected.

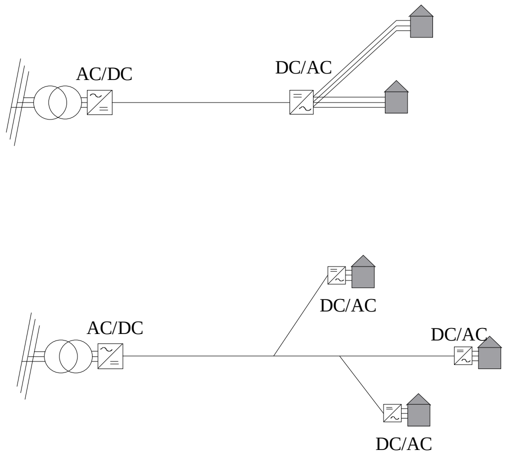
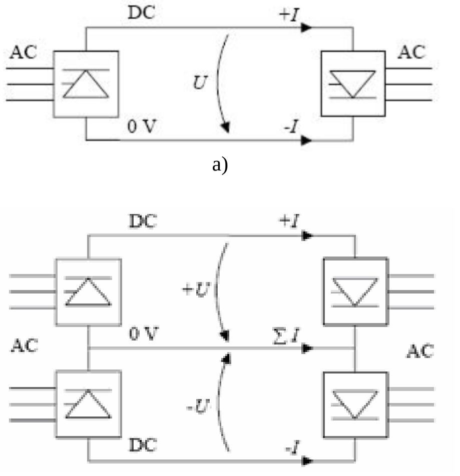


Fig 1. Two different LVDC distribution network topologies.



a)

b)

Fig. 2. DC distribution network with a) unipolar and b) bipolar transmission lines.

The LVDC distribution network is a two- or three-wire system. The two-wire system is called unipolar system, and there is only one voltage level used in the power transmission. The three-wire system is a bipolar system, in which two voltage amplitudes are similar but of the opposite sign. Between these levels, there is a common zero potential [6]. These two DC link alternatives are presented in Fig. 2. The voltage levels in both topologies depend on the techno-economical solutions in the entire system [6]; however, the issue is outside the scope of this paper.

II. COMPARISON BETWEEN AC AND DC SYSTEMS

As presented above, with the use of higher AC voltage levels, the transmission capacity can be improved. With DC, this capacity can be further increased. The main reason is the higher voltage level allowed, because the effective value with the DC voltage can be 1500 V, when it is 500 V less with the AC. Also some other losses can be reduced by using the DC voltage. The inductance of the transmission line does not have an impact in the steady-state condition, when the voltage drop in the line is smaller. There is also no skin effect with DC, which reduces the transmission line resistance and decreases the voltage drop on the line.

The output voltage of the inverter has to satisfy the same standards that define the low-voltage at the customer-end. The Standard SFS-EN 50160 [7] defines, for example, the following requirements for the voltage:

Frequency
- 50 Hz ± 1 % 99,5 % of the year

Voltage level and fluctuation
- 230 V ± 10 %

Harmonic distortion
- THD < 5 %

When an AC system is used, all the above values depend on the whole AC network, and a customer cannot easily affect any of these parameters. A low voltage level is a problem in some sparsely populated areas, where transmission lines are long and transmission losses high. There is also a problem with losses in some older houses and especially in apartment houses, where cables installed decades ago are not able to transmit the increasing power; nowadays, for instance home entertainment needs more and more power. It is very expensive to replace all the cables by thicker ones, and furthermore, it is not possible in practice to use higher AC voltage levels, because a 50 Hz transformer is physically large and expensive and cannot be installed in every apartment. With the DC transmission, it is possible to use same cables and transmit more power, and the DC/AC conversion requires less space than the transformer.

With the DC transmission, it is also possible to improve the customer-end power quality. The main reason is the DC link voltage level, which is notably higher than the level required for the inverter: the minimum is 325 V for the single-phase and 565 V for the three-phase system. The inverter in the customer-side is able to maintain the voltage level and the distortion at the defined values, even if the DC link voltage varies, as long as the voltage is above the minimum value. These minimum values are so low that the voltage reduction has to be very high to affect the inverter operation. With the DC distribution system, customer-end voltage dips and fluctuations can be reduced compared with the traditional AC system, as long as the voltage in the DC link is above the minimum level. It is also possible to eliminate power outages that result from reconnections in the electrical power system, but this requires some energy storages to supply the inverter or inverters during the loss-of-mains situation. These energy storages can be directly connected to the DC link, and it is possible to use a common storage for all inverters or a separate storage for every inverter. This also makes it possible for a customer to individually select the size of the energy storage.

III. SINGLE-PHASE INVERTER TOPOLOGIES

When constructing a low-voltage DC distribution system, the customer-end inverter topology has to be chosen so that it best meets the given requirements. Normally, three-phase power is not needed in most residential applications, because most of the customer loads are single-phase. These loads connected to the three-phase inverter require an inverter with a neutral point. The inverter also has to be designed to work with unbalanced loads, because a balanced load cannot be guaranteed in every operation point. Therefore, the inverter output filtering and switches have to be oversized so that the component limits are not exceeded during unbalanced operation. This leads to a situation where a single-phase inverter should be used to supply such loads, and a three-phase inverter is only used for three-phase loads without neutral. Normally, these three-phase loads are small motors, for example in A/C and ventilation systems. It is possible to use commercial inverters with some changes and simplifications to supply these loads.

A. *Half-bridge topology*

In this paper, two single-phase topologies are discussed. There are two topologies that are typically used in single-phase applications: a half-bridge and a full-bridge topology [8]. The benefits of the half-bridge inverter are its easier controlling and lower costs, as there are only two switches, T1 and T2. The half-bridge inverter can be controlled by switching T1 and T2 in turn. The output voltage depends on the duty cycle D, which depends on the modulation ratio D. As can be seen in Fig. 3, between the two capacitors C1 and C2, there is an output neutral point, and the voltage over these capacitors is +/-0,5 * U_{DC}. Therefore, a maximum output voltage u_{out} is 0,5 * U_{DC}. When 230 VAC is needed, the peak value is 325 VDC and then the minimum DC link voltage needed is 650 VDC. This is not a problem if the DC link is implemented using a unipolar network topology, where the maximum voltage level can be 1500 VDC. When a bipolar network is used instead, the maximum voltage between 0 V and +DC (or -DC) is 750 V. This can be a problem in some applications, because there is only a small voltage reserve for abnormal situations.

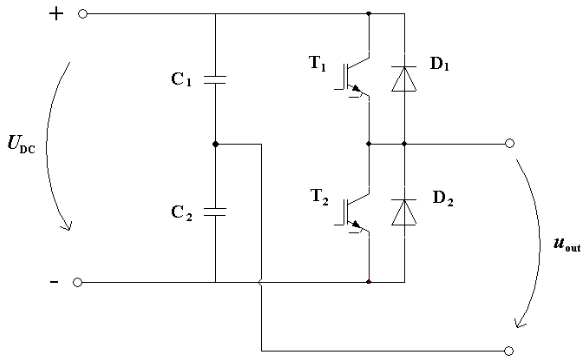


Fig.3. Half-bridge inverter.

Capacitors C1 and C2 store and transfer energy to the load when the T1 or the T2 is switched on. There has to be enough energy in both capacitors to feed the load during the half-period, which is 10 ms with a 50 Hz frequency. This is a quite long time, and capacitances have to be large, particularly when the inverter nominal power *P* is high. If the capacitances are too small, the voltage decreases during the half-period, and thus, it is not possible to reach the required output voltage level. Figure 4 presents the half-bridge inverter output waveform with two different capacitances. The inverter output voltage is filtered with an LC filter. As can be seen in Fig. 4a, capacitor voltages C1.V and C2.V start to fluctuate sinusoidally, and after two periods, the voltages reach the steady-state condition. The sizes of the capacitors are at their minimum, because the output voltage level at some points is the same as the capacitor voltage.

The smallest capacitance can be achieved when the modulation ratio of the inverter is 1. Because of the output voltage quality requirements, overmodulation should be avoided. When choosing the capacitor value, one has to bear in mind that the DC link voltage is not at the maximum value all the time. By choosing a small capacitor value, the advantage of the high DC link voltage will be lost. This leads to a situation where the best choice for the capacitance value is so high that the capacitor voltage and the DC link voltage fluctuation do not affect the output voltage. In Fig. 4b, the capacitance is five times the capacitance of Fig. 4a. As we can see, the capacitor voltage fluctuation is smaller, and there is a larger margin between the output and the capacitor voltage. There is a difference between the output maximum value and the capacitor voltage, and thus the DC link voltage variation is possible.

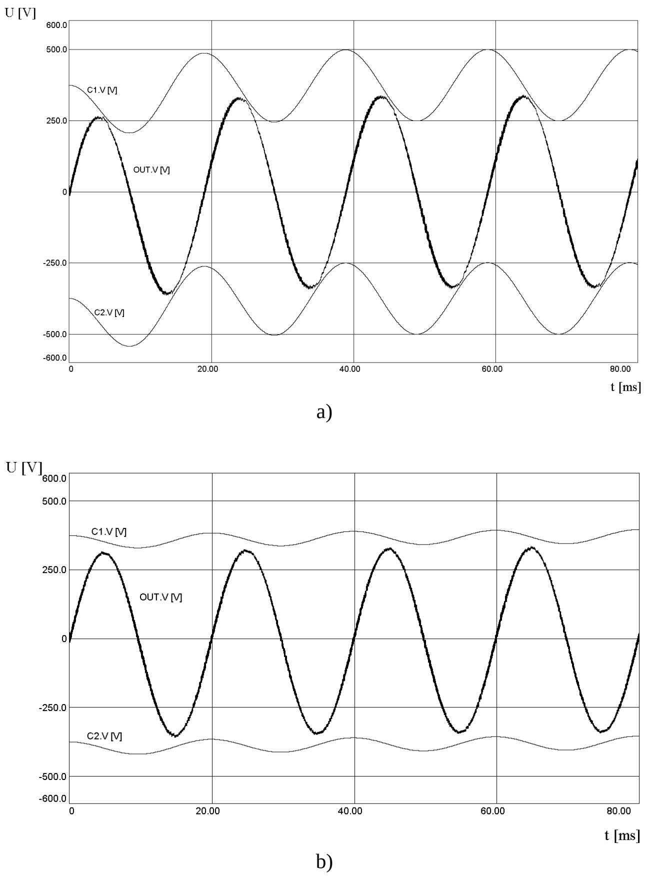


Fig.4. Inverter output voltage and capacitor voltages with a) small and b) large capacitances.

Capacitance values can be calculated when the inverter nominal power is known. Capacitors are identical, and thus only a one capacitance calculation is needed. The required energy during a half-period of the output voltage is

$$W = Pt = \hat{u} \cdot \hat{\imath} \int_{0}^{0.01} \sin(\omega t) \tag{1}$$

The energy in the capacitor is

$$W_{\mathrm{C}} = \frac{1}{2} C U^{2} \tag{2}$$

As we can see in Fig. 4, the capacitor voltage is at its maximum when it starts to supply the load, and at the minimum after one half-period. The energy cannot be calculated using only the capacitor voltage at the time *t* = 0 s and *t* = 0.01 s, because the DC link charges the capacitor during the switch off-time. Hence, for exact calculations, it is necessary to calculate the capacitor energy in every switching, which is very time consuming. However, the capacitance value can be approximated using the maximum and the minimum capacitor voltage and the inverter modulation ratio

M. This method gives a somewhat pessimistic capacitance value, because the capacitor charging is not taken into account as precisely as in every switching calculation.

The capacitor voltage maximum value $U_{\mathrm{max}} = U_{\mathrm{DC}} / 2 + U_{\mathrm{fluc}}$ and the minimum value $U_{\mathrm{min}} = U_{\mathrm{DC}} / 2 - U_{\mathrm{fluc}}$. When $W_{\mathrm{C}} = W$, we get

$$C' = \frac{2 \cdot \hat{u} \cdot \hat{i} \int_{0}^{0.01} \sin(\omega t)}{U_{\mathrm{max}}^{2} - U_{\mathrm{min}}^{2}} \tag{3}$$

The switch duty ratio varies from 0 to $D_{\mathrm{max}} = M$, and the capacitor energy is supplied to the load during the switch on-time. Because the duty ratio follows a sinusoidal waveform [8], the RMS value of the duty ratio can be used in the calculations. Using (3) and the duty cycle RMS value, we get

$$C = \frac{C'}{\frac{D}{\sqrt{2}}} = \frac{C'D}{\sqrt{2}} \tag{4}$$

For example, in the simulation (Fig 4a.), the capacitance values are 800 uF, P = 10 kVA, U_{DC} = 750 V, M = 0,89, and U_{fluc} = 125 V. When we calculate the capacitance using (1) – (4), we obtain $C \approx 855$ uF. A capacitor with such a high capacitance is physically large and expensive, because the voltage rating has to be at least 500 V. One should also bear in mind that this is the minimum capacitance value, which in practice should be increased so that the capacitor voltage would be high enough in every situation. The inverter also has to supply a sufficient short-circuit current, which further increases the capacitor size.

The physical size of the capacitors has to be taken into account when designing a customer-end inverter. There is no technical room in most of the apartments, and therefore the size of the inverter has to be as small as possible. The capacitors of this kind are also electrolytic, and they are not durable enough for this application; the inverter is in use 24/7, and its lifetime should be at least ten years. Large electrolytic capacitors have to be replaced during the inverter lifetime, which increases costs. Furthermore, the capacitors are not identical, and thus the voltage might not be the same in both capacitors. This makes the inverter control and stability more complicated. The capacitance can be reduced by increasing the DC link voltage, but the maximum capacitor voltage is 750 V, because the DC link maximum voltage is 1500 V. Now, the capacitor voltage rating increases, which increases the physical size. Judging from these drawbacks, electrolytic capacitors are not suitable for this application, and therefore, there is no need for exact capacitance calculations. To sum up, a half-bridge inverter is not a viable techno-economical solution for low-frequency applications.

B. *Full-bridge inverter*

Large capacitances in a half-bridge inverter can be avoided by using a full-bridge topology [8]. In the full-bridge inverter (Fig. 5.), capacitors are replaced with switches T3 and T4. With four switches, the DC link directly supplies the load, and there is no need for physically large capacitors. However, there has to be some capacitance in the DC link to provide fast energy to switches. With four switches, the maximum output voltage of the full-bridge inverter is $+U_{\mathrm{DC}}$, which is double compared with the half-bridge inverter. This is an advantage, because the higher voltage level allows more variation with no changes in the customer-end voltage. With the higher voltage, it is also possible to reach higher short-circuit currents, which is necessary for meeting the electrical safety requirements.

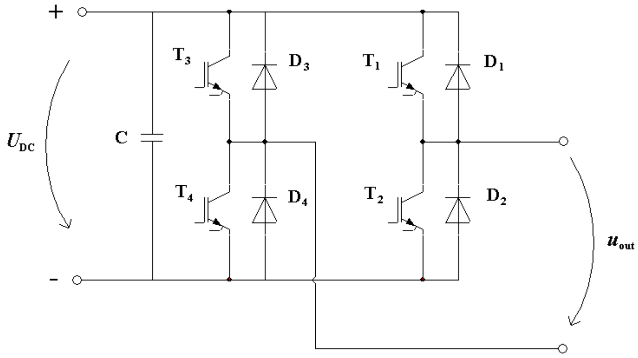


Fig 5. Full-bridge inverter.

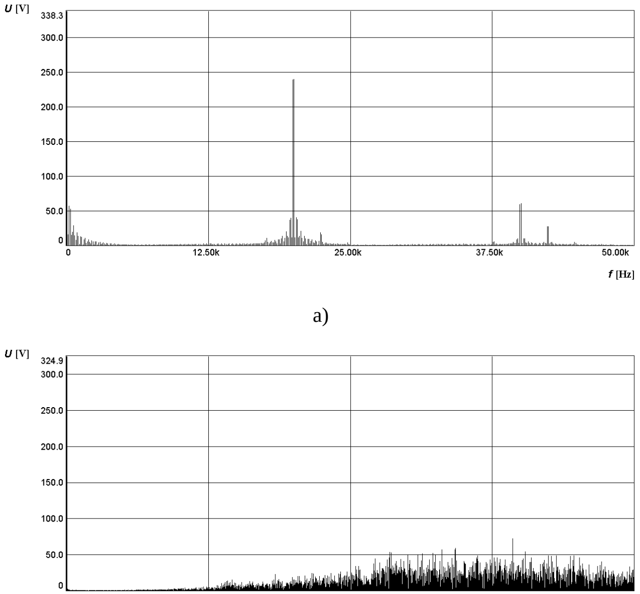
1) *Full-bridge inverter modulation*

There are two PWM switching schemes for the full-bridge inverter: unipolar and bipolar modulation [8]. In the bipolar modulation, crosswise switches are controlled similarly as in the half-bridge inverter. Hence, also the output voltage has only two levels, but the voltage maximum value is twice compared with the half-bridge. Two voltage levels make the output voltage control more inaccurate, and the inverter requires more effective filtering. The first harmonic of the output voltage is also at the switching frequency f_{sw}, the effect of which is considered next.

With a unipolar switching scheme, the output voltage in the full-bridge inverter is $+U_{\mathrm{DC}}$, 0 or $-U_{\mathrm{DC}}$. The zero voltage level enables a more accurate voltage control, which increases the voltage quality and makes the output voltage filtering easier. Smaller filter components also cost less and require less space. A further advantage of the unipolar modulation, which has an effect on the filtering, is that the scheme effectively doubles the switching frequency, while the actual switching frequency remains unchanged [8]. Then, the lowest harmonic in the output voltage harmonic spectrum is twice the switching frequency. This can be seen in Fig. 5a, where f_{sw} = 10 kHz and the first harmonic is at 20 kHz. When the first harmonic frequency is double, the output voltage filter can be designed using this double frequency, which reduces the size of the filter components and reduces costs.

A full-bridge inverter can also be controlled without PWM. Basically, in a hysteresis modulation, the inverter switches on only when necessary. The output voltage is measured and compared with the reference voltage waveform. It is possible to control the switches either bipolarly or unipolarly. In the bipolar modulation, the output voltage levels are $+U_{DC}$ and $-U_{DC}$, while in the unipolar one, they are $+U_{DC}$, 0 and $-U_{DC}$. According to the modulation selected, the most adequate level is switched to the load depending on the current output voltage level.

When using a hysteresis modulation, there is no constant switching frequency, but only the maximum f_{sw} value. This maximum value depends on the minimum time step of the controller. Figure 5b presents the output voltage harmonic spectrum of the hysteresis-modulated inverter. We can see that there is no single harmonic as in Fig. 5a, but there are many different frequency components.



a)

b)

Fig 5. Output voltage harmonic spectrum with a) unipolar PWM modulation and b) hysteresis modulation.

IV. INVERTER REQUIREMENTS

Single-phase inverters are commonly used in UPS systems. In these devices, the efficiency and the power quality at low output powers are not known; specifications are given only at the nominal output power. In this application, the efficiency at the nominal power is not the main design boundary condition. The efficiency throughout the output power has to be as high as possible in every operation mode, because the techno-economical potential of the whole DC distribution network depends largely on it. The output power of the customer-end inverter may vary from zero to the rated power, and the inverter may run at a partial load for a long time. This makes the inverter control and component selection a challenging task.

In Fig. 6., two examples of inverter efficiency curves as a function of output power are presented. In the customer inverter, high output powers are not frequently used. Hence, the efficiency that follows the curve 2 is not as an economical choice as the one presented by the curve 1, even though the efficiency at high output powers is better. In every implementation, the inverter efficiency curve has to be optimized based on the customer load curve. This can also lead to a situation where there is not one large but several smaller inverters with lower nominal powers. In these inverters, switches with lower current ratings can be used to decrease the switching losses. These inverters are started up one by one when the power requirement increases. However, multiple inverters have more components, and they require more space. There are many factors affecting the selection of the inverter size, yet the target in any case is to reach the best possible energy efficiency.

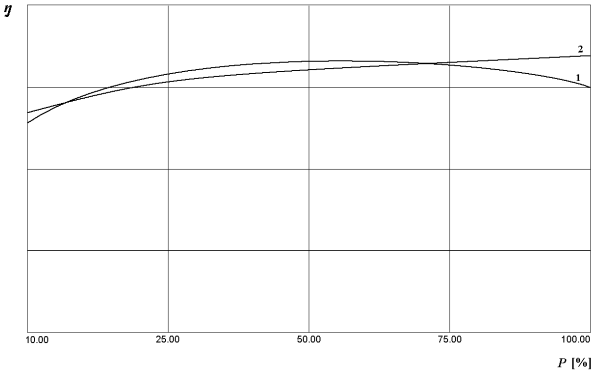


Fig 6. Two different inverter efficiencies as a function of output power.

The switching scheme of the inverter also affects the selection of the inverter output filter structure. With the PWM modulation, the output filter components depend largely on the switching frequency: the higher the frequency, the smaller the filter components. However, transistor switching losses are directly proportional to the switching frequency, which limits the frequency, and it is of course not economical to increase losses.

Switching losses also depend on the transistor current, as shown in Fig. 7, which presents the switching energies E_{off} and E_{on} of an IGB transistor as a function of collector current I_C. We can see that the switching energies at the lower current are low. This enables the use of a load-dependent variable switching frequency. With the variable frequency, the output filter can be designed for a higher power, and the poorer filtering at a lower power can be compensated using higher switching frequencies. A variable switching frequency can only be used with the PWM modulation, because the hysteresis modulation has no fixed frequency. The selection of filter components, the modulation, and the switching frequency is not simple, as they all depend on many different factors. The inverter efficiency and requirements are not widely studied; therefore, more precise analyses are required.

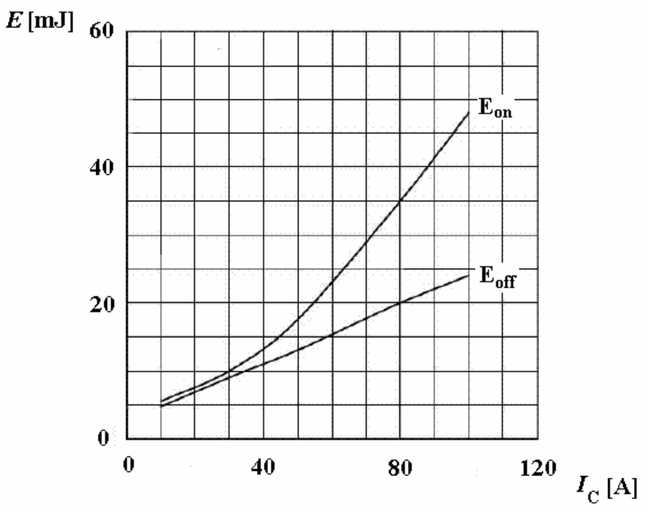


Fig. 7. Turn-on and turn-off energies E_{on} and E_{off} of an IGB transistor as a function of collector current I_C.

When applying the PWM switching scheme, the constant switching frequency creates a constant audible noise. A part of the noise comes from the switches, but the main sound source is the oscillating choke core. When the inverter is installed inside an apartment, the noise of the inverter has to be low enough. The easiest way to solve the problem is to increase the switching frequency so that the first harmonic output harmonic frequency is above the audible frequency. One has to bear in mind that the highest frequency that a human being can hear is not high enough, because the audibility range of many pets exceeds this level. The inverter cannot create stressful noise. In this case, the unipolar PWM modulation is a better choice; with it, the switching frequency doubling quadruples the first output voltage harmonic frequency. With the bipolar modulation or with the half-bridge inverter, the first harmonic frequency only doubles. However, we should remember that the switching losses increase at the same time. This might not be a problem in the future, when high-efficiency switching components are available, but nowadays, the only alternative for this type of an application is an IGB transistor. The amount of noise can also be decreased by an appropriate filter choke core material; this, however, usually leads to higher costs.

As has been shown above, with the hysteresis modulation, the output voltage frequency spectrum has no single high-amplitude frequencies, but there are many small-amplitude frequencies instead (Fig. 5b.). Therefore, there are several components in the audible range, which makes the sound less irritating: a single-frequency sound turns into noise. When there are no single frequencies, the hysteresis modulation frequencies do not have to be above the audible range.

V. CONCLUSION

The power quality and reliability can be improved by using LVDC distribution. In this paper, because of the little need for three-phase power, two single-phase inverter topologies are described. The results show that a half-bridge inverter is not suitable for this kind of an application because of the large capacitors needed. A full-bridge inverter should be used instead. The inverter modulation should be selected such that the output voltage requirements are met in all operation situations, and the inverter efficiency is high even if the load changes.

REFERENCES

[1] European Commission. Low Voltage Directive LVD 2006/95/EC. European commission directive: Brussels, 2006.

[2] Lohjala, J. “Development of rural area electricity distribution system – potentiality of using 1000 V supply voltage”. Ph.D. dissertation, Dept. of Elect. Eng., Lappeenranta Univ. of Tech., Lappeenranta, Finland, 2005. (in Finnish.)

[3] Kaipia, T., Salonen, P., Lassila, J., Partanen, J. ”Possibilities of the Low Voltage DC Distribution Systems”. In proceedings of the NORDAC Conference 2007.

[4] Kaipia, T., Salonen, P., Lassila, J., Partanen, J. “Application of Low Voltage DC-Distribution System – A Technoeconomical Study”., 2007.

[5] Partanen, J. & al. ”Power Electronics in Electricity Distribution, Phase 1/2”, Project report, in Finnish, Dept. of Elect. Eng., Lappeenranta Univ. of Tech.., Lappeenranta, Finland, 2008. (in Finnish)

[6] Salonen, P., “Exploitation Possibilities of DC in Electricity Distribution”, Master’s thesis, Dept. of Elect. Eng., Lappeenranta Univ. of Tech., Lappeenranta, Finland, 2006. (in Finnish)

[7] SFS-EN 50160. Voltage Characteristics of Electricity Supplied by Public Distribution Systems. National standard. SESKO Standardization, Finland, 2007. VUOSI?

[8] Mohan, N., Undeland, T., Robbins, W. P., “Power Electronics - Converters, Applications and Design”. 3rd Edition, Wiley, 2003.